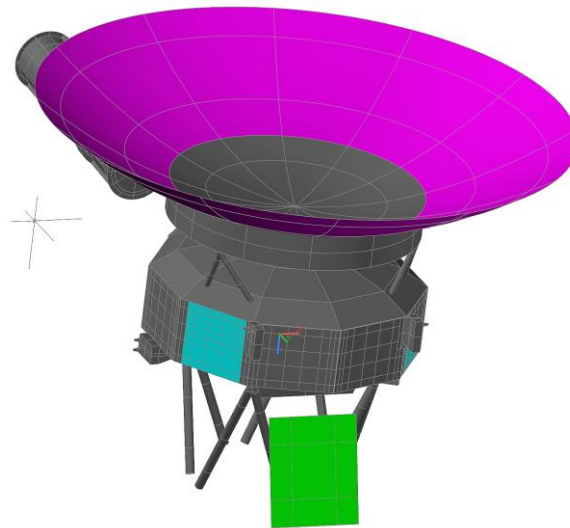# Creating a Voyager Thermal Model 39 Years Into the Flight Mission, Along With Model Correlation and Application

ICES Paper 2018-134

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Agenda

- Introduction

- Mission Overview / Running Out of Power...

- Propulsion Module Subsystem (PMS) Thermal Design

- Approach to Building Model / Model Development

- Model Correlation

- Application to Voyager Flight Operations

- Conclusions / Lessons Learned

Introduction

- 41-year old Voyager spacecraft are running out of power.

- To preserve the mission and continue science, hard choices need to be made.

- How to keep the propellant lines from freezing?

- How to model a spacecraft from scratch?

- How to correlate a spacecraft model without test data?

- This paper tells the story of how these goals were and are being met.

Mission Overview

The Voyager spacecraft, each carrying 10 science instruments were launched 41 years ago to explore the outer planets and beyond…
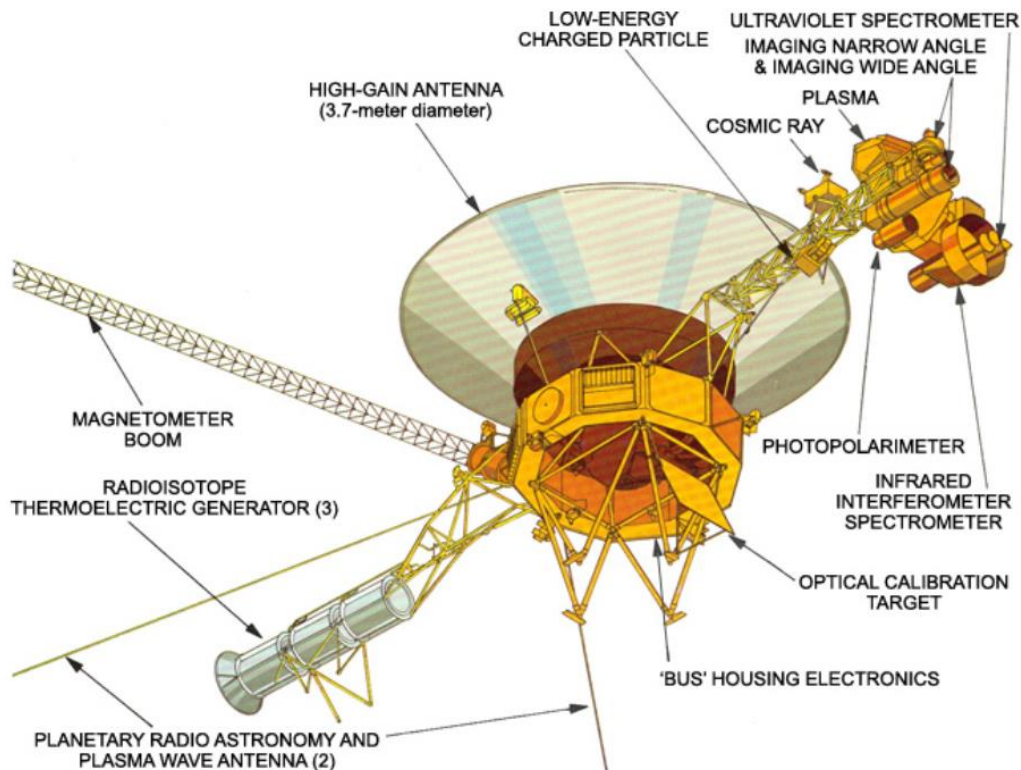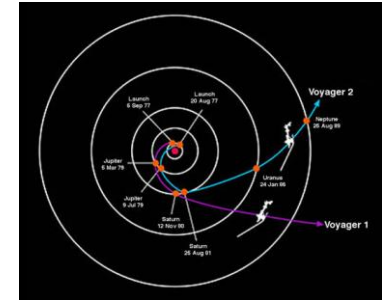
Instrument List

- 'BUS' Housing Electronics
- Cosmic Ray Subsystem (CRS)
- High-Gain Antenna
- Imaging Science Subsystem (ISS)
- Infrared Interferometer Spectrometer and Radiometer (IRIS)
- Low-Energy Charged Particles (LECP)
- Magnetometer (MAG)
- Optical Calibration Target
- Photopolarimeter Subsystem (PPS)
- Planetary Radio Astronomy (PRA)
- Plasma Science (PLS)
- Plasma Wave Subsystem (PWS)
- Radioisotope Thermoelectric Generators (RTG)
- Ultraviolet Spectrometer (UVS)

Running Out of Power…

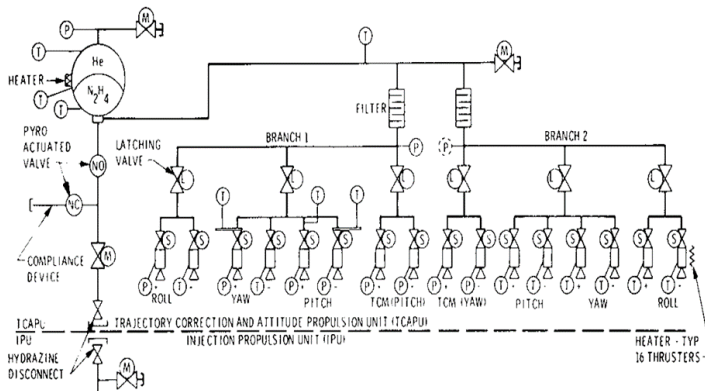- Each spacecraft carries three Radioisotope Thermoelectric Generators (RTGs).

- These power all of the on-board science and engineering functions.

- As the graph shows, by Fall of 2020 the Voyager 2 (S/C 32) power margin will have dropped to 2 W.

- For the mission to continue, some function(s) must be turned off before the power margin gets that low.

[1] PSTAT is software used to calculate RTG power from telemetry.

S/C 32 Total RTG Power At RTG Toggle Points

Watts — S/C 32 PSTAT[1] RTG's Actual Tlm (2006-2017 and Predicted (2006-2032) Total RTG Power

247.69 W RTG Total Power as of 2017-225

237 W Required for S/C, Science Instruments and 2 W of Power Margin 2020-262

201 W End Of Mission 2031-230
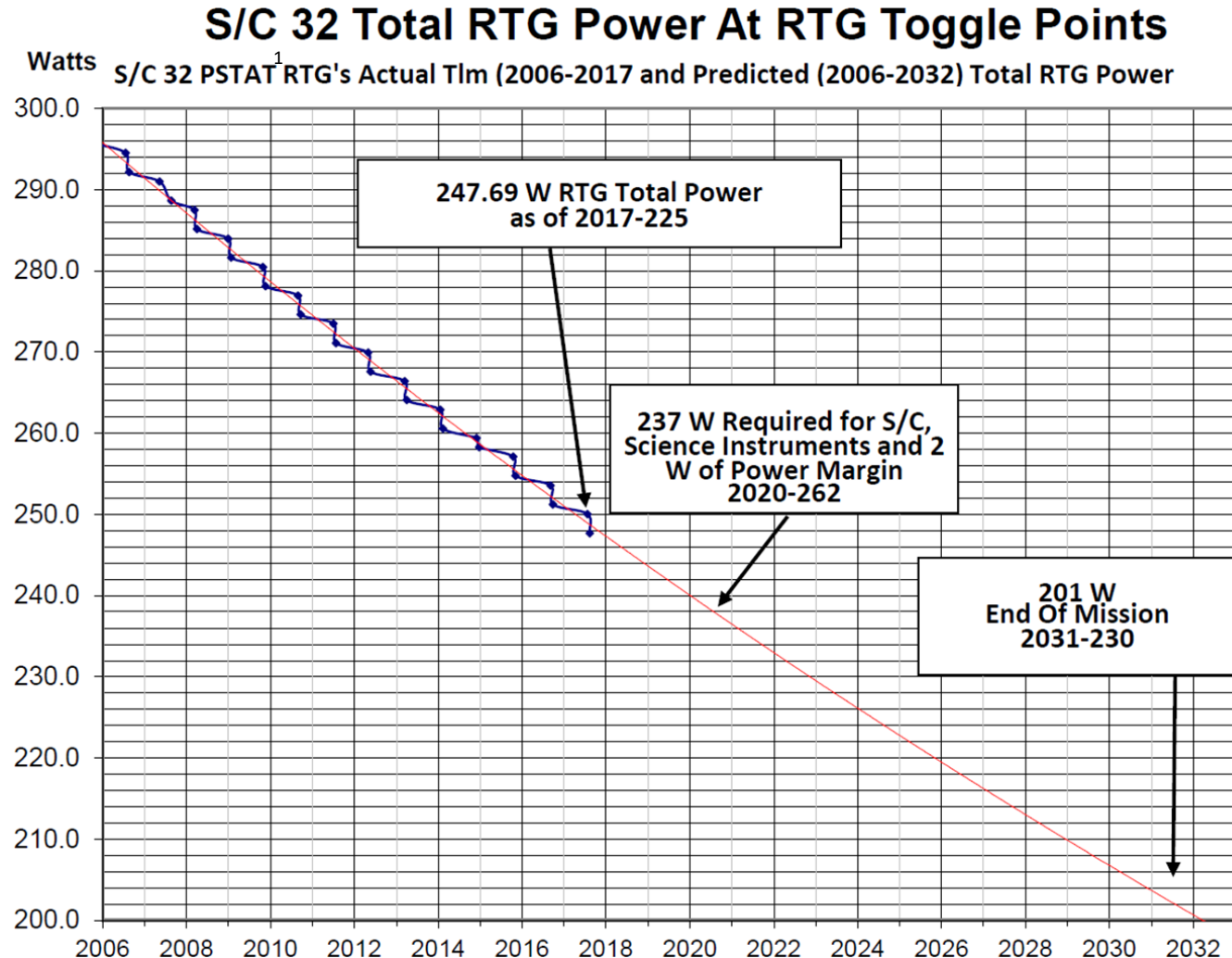
Propulsion Module Subsystem (PMS) Thermal Design

- Fuel Tank positioned at center of spacecraft bus.

- Blow-down monopropellant (hydrazine) flows through stainless steel lines, filters and valves to reach each of the 16 thruster/valve assemblies (T/VAs).

- Propellant lines routed in-plane, directly beneath spacecraft bus.

Challenges of Building Model From Scratch

- No pre-existing model in digital form.

- 237 drawings were scanned from Vellum File paper drawing archives into PDF format.

- Many photographs of the full-size Voyager model in von Karman auditorium at JPL were also used as guides for building the thermal model.

Bus and Propulsion Module Subsystem (PMS)

Thermal Model Development

Table 2. Spacecraft System Drawing Parts List (included in TMM).	
Description	**Rationale**
THERMAL CONTROL INSTALLATION	Includes all louvers, MLI blankets, RHUs, shields and shades on the spacecraft.
RTG INSTALLATION	Radiative interface seen by the bus, MLI on that side of the spacecraft, and louvers. Only external geometry of RTGs modeled. Telemetry of RTG case temperatures used as a boundary condition in model.
ANTENNA INSTALLATION	Also required for accurate radiative and conductive interface.
SPACECRAFT ASSEMBLY	Includes Bus and hardware attached to bus, plus TCAPU and truss.
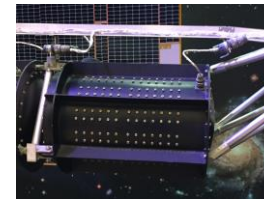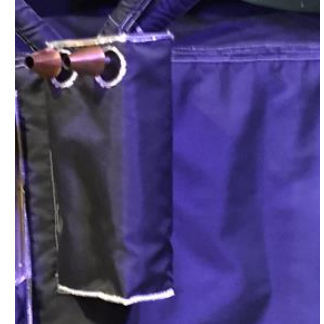
These items were selected for inclusion in the model as they were deemed essential to calculating accurate propellant line temperatures.

Thermal Model Development (cont.)

- The initial correlated thermal model was delivered to the Voyager project in October 2015.

- Over the following year, various refinements were added to the model, including detailed verification of the propellant line geometry aided by photographs of the flight spare Trajectory Correction/Attitude Propulsion Unit (TCAPU), updating the thruster thermal model and adding labeling of the individual Thermal Desktop elements, consistent with nomenclature from the drawings.

Thermal Model Development (cont.)
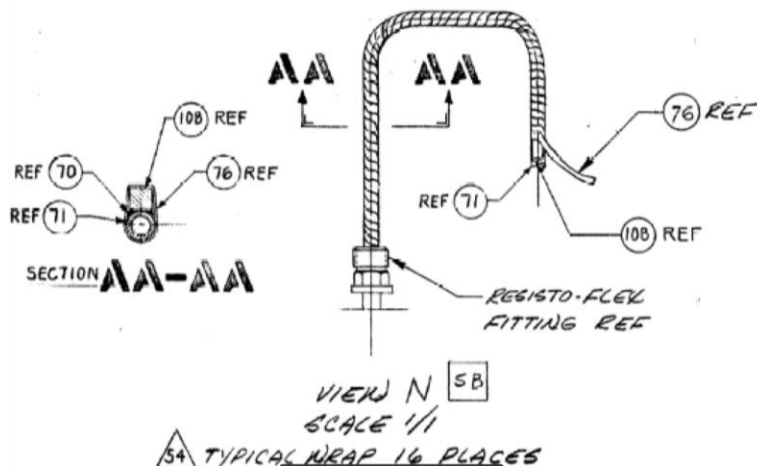
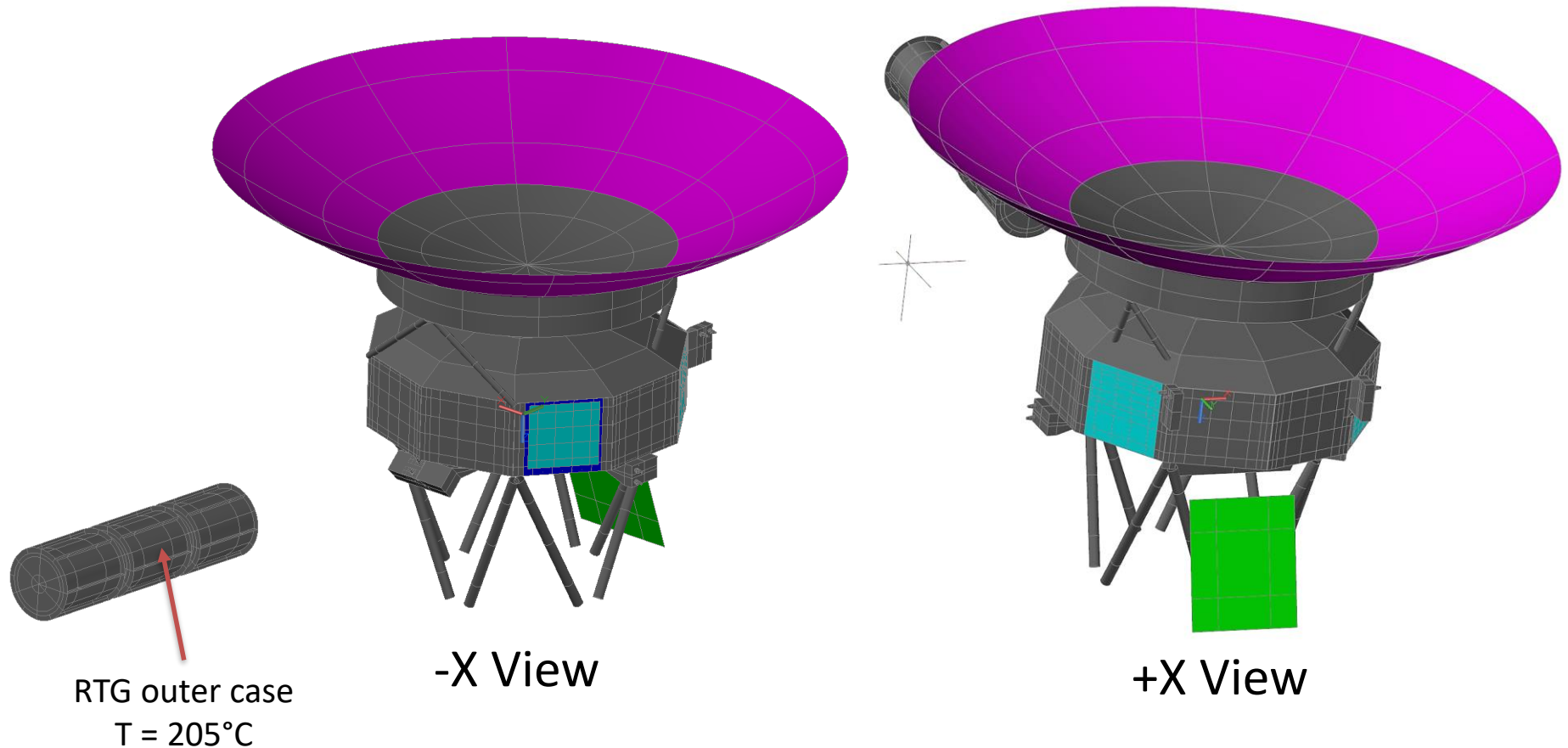Propellant Line "cladding"
(from TCAPU Installation Drawing)

Bonding aluminum 1100-0 alloy bar to stainless steel line increased thermal conductance by >30X near thruster inlets

Platinum Resistance Thermometer (PRT)
(Flight Sensor on +Yaw Thruster Bracket)

Completed Thermal Desktop Model

RTG outer case
T = 205°C

-X View

+X View

**1,177 surfaces and thin-shell elements
4,543 nodes**

Model Correlation / Dataset Selection

- With limited thermal vacuum test data, not representative of current environment, we searched for relatively recent, steady-state flight data to use for model correlation.

- We settled on HOT and COLD cases, both from 2014, although the "hot" condition represented only a 9% increase in bus power dissipation over the "cold" case (212 W vs. 195 W).

- Choice of 2014 datasets ensured model would be correlated in a consistent fashion to the current environment (i.e. no significant solar or planetary heating).

Model Correlation
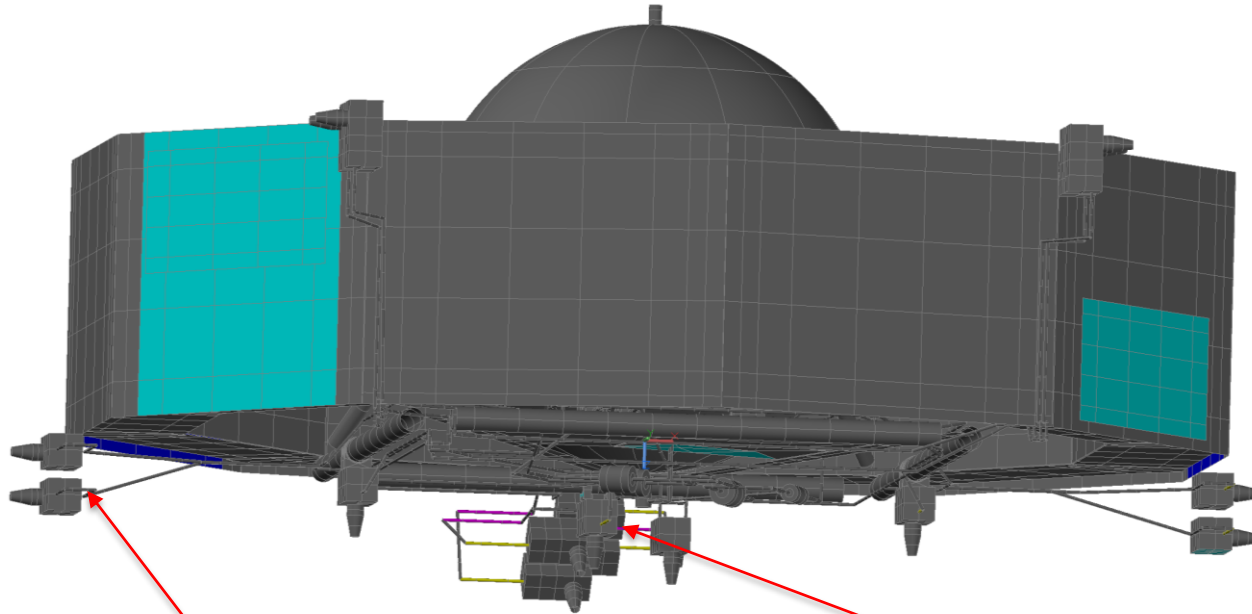
- Model correlation was achieved by adding small heat loads close to the +Yaw thruster bracket (0.02 W) and ±Pitch thruster bracket (0.06 W) to get propellant line temperature predictions to match limited flight data (only 2 sensors directly mounted on propellant lines).

Thermal Model Correlation (Final Results)

Correlated model matched steady-state flight temperature telemetry data for HOT & COLD cases within 5°C.

	2014-343 XB-LO, GYON	2014-247 XB-HI, GYOFF				
	HOT CASE	COLD CASE	HOT CASE	COLD CASE	HOT CASE	COLD CASE
Description	**Flight Data [°C]**	**Flight Data [°C]**	**Predictions [°C]**	**Predictions [°C]**	**Delta [°C] TMM-Flt**	**Delta [°C] TMM-Flt**
Bay 1 Temp	25.8	23.7	24.2	22.6	-1.6	-1.1
Bay 2 Temp	17.6	14.1	19.0	17.3	1.4	3.2
Bay 3 Temp	15.4	11.9	18.8	16.9	3.4	5.0
Bay 4 Temp	13.3	9.7	15.8	13.6	2.5	3.9
Bay 5 Temp	23.4	18.5	22.9	20.7	-0.5	2.2
Bay 6 Temp	25.4	16.9	24.1	15.9	-1.3	-1.0
Bay 7 Temp	20.3	20.3	19.8	19.0	-0.5	-1.3
Bay 8 Temp	13.8	10.3	14.9	11.9	1.1	1.6
Bay 9 Temp	18.0	13.8	18.6	14.5	0.6	0.7
Bay 10 Temp	21.1	19.0	21.8	19.0	0.7	0.0
TCAPU Surface Temp 1	20.5	14.9	18.6	18.7	-1.9	3.9
TCAPU Surface Temp 2	25.0	20.1	25.6	24.6	0.6	4.5
TCAPU Tank Temp 1	15.4	12.6	12.2	9.0	-3.2	-3.6
TCAPU Tank Temp 2	14.8	12.7	11.0	8.0	-3.8	-4.6
TCAPU Feed System Temp 1	12.0	8.5	11.1	9.6	-0.9	1.1
TCAPU Feed System Temp 2	22.0	17.8	17.9	17.0	-4.1	-0.8

Bus

PMS

±5°C

Application to Voyager Flight Operations

- Engineering maneuvers
  - Acquisition Sun sensor Calibration (ASCAL)
  - Thermal Tests
    - Model used to bound excursions of both bus and PMS temperatures during transient activities/tests.

- Science maneuvers
  - Magnetometer Calibration (MAGROL)
    - 2 revolutions about spacecraft Z-axis
    - Performed 2-4 times per year

Application to Voyager Flight Operations (cont.)

- Predictions for decreasing power margin in baseline power state.

- Assessment of proposed changes in steady-state power configuration (e.g. Turning off Digital Tape Recorder (DTR) in Bay 2).

Conclusions / Lessons Learned

- Resources needed to create model from scratch are inversely proportional to data available.

- Good thermal design is essential for mission longevity.

- Investment in archiving project data pays off the longer the mission is extended.

- Correlating a thermal model to flight data when very limited (and possibly ambiguous) test data is available ***can be done.***

- Power ***and*** thermal constraints must now be considered in maintaining Voyager spacecraft health and the ability to collect valuable science data.

Acknowledgments

The author would like to acknowledge the following people for their contributions to the development of this thermal model: